Potravinarstvo Slovak Journal of Food Sciences

OPEN ACCESS

Received: 4.1.2023
Revised: 20.3.2023
Accepted: 21.3.2023
Published: 27.3.2023

Slovak Journal of Food Sciences

Potravinarstvo Slovak Journal of Food Sciences
vol. 17, 2023, p. 324-342
https://doi.org/10.5219/1854
ISSN: 1337-0960 online
www.potravinarstvo.com

Food safety and food security through predictive microbiology tools: a short review

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ABSTRACT

This article discusses the issues of food safety and food security as a matter of global health. Foodborne illness and deaths caused by pathogens in food continue to be a worldwide problem, with a reported 600 million cases per year, leading to around 420,000 deaths in 2010. Predictive microbiology can play a crucial role in ensuring safe food through mathematical modelling to estimate microbial growth and behaviour. Food security is described as the social and economical means of accessing safe and nutritious food that meets people's dietary preferences and requirements for an active and healthy life. The article also examines various factors that influence food security, including economic, environmental, technological, and geopolitical challenges globally. The concept of food safety is described as a science-based process or action that prevents food from containing substances that could harm human health. Food safety receives limited attention from policymakers and consumers in low- and middle-income countries, where food safety issues are most prevalent. The article also highlights the importance of detecting contaminants and pathogens in food to prevent foodborne illnesses and reduce food waste. Food and Agriculture Organization (FAO), an institution belonging to World Health Organization (WHO) presented calls to action to solve some of the emerging problems in food safety, as it should be a concern of all people to be involved in the pursue of safer food. The guarantee of safe food pertaining to microbiological contamination, as there are different types of active microorganisms in foods, could be obtained using predictive microbiology tools, which study and analyse different microorganisms' behaviour through mathematical models. Studies published by several authors show the application of primary, secondary, or tertiary models of predictive microbiology used for different food products.

Keywords: food safety, food security, predictive microbiology

INTRODUCTION

According to the World Health Organization (WHO), around 600 million cases of foodborne illness are reported around the globe every year. The number of deaths in the year 2010 was estimated to be around 420,000 people, and such a number tends to increase year after year due to the difficulty of estimating statistics on foodborne diseases **[1]**. Several agents are responsible for these infections, such as chemicals, parasites, and pathogenic and spoilage microorganisms **[2]**. Food safety refers to processes or actions that prevent foods from containing substances that could harm one's health and is designed to guarantee safe food for consumption. With the assurance of safe food, food security is improved by reducing hunger and malnutrition **[3]**, **[4]**. The quality and safety of foods can be determined through predictive microbiology, which uses mathematical modelling to estimate microbial growth and behaviour **[5]**. Many are applications of predictive microbiology in the food cycle production to guarantee safe food, from risk assessment to employee training. The result from its mathematical modelling helps to prevent foodborne illness outbreaks **[6]**, **[7]**. This review aims to introduce and discuss the concepts of food safety and food security as a matter of world health issue, and the use of predictive microbiology through its models, which could be a tool to prevent food contamination and foodborne illness diseases.

FOOD SAFETY AND FOOD SECURITY

Food Security: According to the Food and Agriculture Organization (FAO), food security occurs when people have the social and economical means to physical access to safe and nutritious food that meet their dietary necessities and preferences for the maintenance of an active and healthy life, at all times **[8]**, **[9]**. Food security has a new reality where several factors influence the access of all people to safe food, being economic, environmental, technological, and geopolitical challenges globally **[10]**, **[11]**.

FAO/UNICEF described food security with the perception based on four main concepts: food availability; physical and economic access to food; food usage, based on cultural and nutritional requirements; and food stability, as the balance of supply (Figure 1) **[8]**.

Figure 1 The four pillars of food security (Adapted from **[8]**).

Between 1961 and 2000, an exponential increase in the global population demanded developments in food production. Scientific and technological progress, government actions, institutional interference, business investment and innovation were able to meet the requirements **[8]**. The United Nations predicts an increase in global population annually of 0.96% from 2015 – 2030 and 0.63% between the years 2030 – 2050, reaching approximately 9.7 billion people by the year 2050. This population rise is expected to occur mostly in lower-income and less-developed countries **[8]**, **[10]**, **[12]**.

Some global megatrends are expected to meet the safe food requirements for all within the next years. Food production "industrial-scale and centralized production systems, together with large-scale farming, intense animal production, and large-scale food process and distribution" **[12]** continuously increased in the last few years. Climate change can also affect food security in many aspects, so the need for actions to be taken will most likely address some of the current problems in that area. Mega-cities and mega-regions could facilitate people's access to modern food chains and supermarkets, supplying safe food. The growing ageing population demands "extra-safe food", the impacts food can have on their welfare is a matter of public health. One of the trends is also technologically web-based food, the printing of food in 3D printers could revolutionize the food industry. At last, as consumers desire individualized food, nutrition, service, and experiences, new products and innovations will emerge to satisfy those needs **[12]**, **[13]**.

Food safety: Food safety refers to how food is handled, prepared, and stored to minimize the risk of contamination. FAO (2022) describes food safety as a "science-based discipline, process or action that prevents food from containing substances that could harm a person's health, aiming to have safe food". Furthermore, improving food safety decreases hunger and malnutrition, associating safe food with food security **[14]**, **[15]**.

Food is the most basic human need, coming in third place after air and water, and is a necessity for everyone, meaning everyone should be involved in the pursuit of safer food. Those involved in growing, harvesting, transporting, processing, and packing food, also consumers and people responsible for providing laws, regulations, institutions, and inspections, should guarantee the production of safe and nutritious food for all **[16]**, **[17]**, **[18]**.

Most safety issues can be observed among low- and middle-income countries (LMIC) and could be related to poor infrastructure and lack of information on food handling, causing pathogenic contamination. Food safety receives limited attention from policymakers and consumers in LMICs. Governmental institutions often in charge of these functions in such countries deal with a problem with funds and other constraints, reducing and restraining any action **[19]**, **[20]**.

Also, disadvantaged and underprivileged populations are less willing to pay for safer food, probably due to low knowledge, than those with a higher income. According to studies, low-income and marginalized populations in Europe and the USA presented higher incidences of foodborne illnesses **[19]**, **[21]**, **[22]**.

Contaminants that present as a hazard to food safety if not detected prior to consumption include heavy metals, veterinary residues, pesticides, environmental organic residues, mycotoxins, microorganisms, and many others. Food spoilage can also be considered a food safety concern, contributing to food waste and food poisoning. Approximately one-third of all food produced (1.3 billion tons per year) is wasted globally **[23]**, **[24]**.

Antibiotic resistance is one of the most pressing issues in food safety. Antibiotic-resistant microorganisms that could cause diseases are becoming more prevalent. Enteric viruses provide a significant hazard to the spread of foodborne illnesses. Unintentional chemical pollution is dangerous for both people and wildlife. Food adulteration, motivated by economic factors, has a terrible impact on health. Around 3.5–4% of the world's population suffers from allergies and intolerances; nanotechnology is still under investigation but may pose risks to food production; genome editing may have an impact on global food production; and there may be a need for food safety regulations in this area **[12]**, **[25]**.

According to the SPS Agreement, which was established by the World Trade Organization (WTO) in 1994 to determine sanitary and phytosanitary procedures to protect public health in a way that causes the least amount of trade disruption, preventive actions in food safety systems should follow key criteria, such as systematic; risk-based, following a set of priorities and risk management methods; being open and participatory; being cost-effective; and causing the least amount of trade disruption. How institutions work together also impacts outbreak management success, as food safety is equally an institutional challenge as it is academic and scientific, corporate, or legislative **[26]**, **[27]**.

WHO, with FAO in 2021, organized the campaign "World Food Safety Day 2021" with the theme "Safe food now for a healthier tomorrow", uniting the community globally to aid in the prevention, detection, and management of foodborne illness with actions presented in Figure 2 **[3]**.

Figure 2 Calls to action on food safety (Adapted from **[3]**).

MICROBIOLOGICAL ASPECTS

In fresh products, a series of microbiological, enzymatic, chemical, and physical reactions occur, simultaneously or consecutively, during storage time **[28]**, **[29]**, **[30]**. Product features determine the predominance of one spoilage effect over the other production activities, packaging, and storage conditions, among other factors **[31]**, **[32]**, **[33]**, **[34]**, **[35]**, **[36]**.

The analysis is carried out through comprehensive monitoring of variations in the critical indicator when the product is stored under specific circumstances, and considering the deterioration caused by microorganisms, simultaneously evaluating changes in sensory and physicochemical characteristics **[37]**, **[38]**, **[39]**.

Microorganisms: Microorganisms present in food are divided into three categories:

- Technologically beneficial: added to foods to enhance technological and sensory qualities. Selected microorganisms are added to preserve and extend the product's shelf life **[40]**.
- Foodborne pathogen: produces toxins and infects living cells, causing foodborne disease. These microbes can be found in the product's flora or can be transferred to food by contamination during processing, storage, or transportation **[41]**, **[42]**, **[43]**.
- Deteriorating microorganisms: create sensory changes in the product's colour, odour, flavour, and texture due to microbial proliferation and metabolism **[44]**, **[45]**.

Due to the severity of diseases caused by pathogenic microorganisms, a minimum limit or absence in food products is estimated to avoid foodborne illness epidemics **[46]**, **[47]**. The behaviour of spoilage microorganisms represents a challenge for shelf-life determination as they cause physical, chemical, and biological changes, making the food unpleasant to the human senses and unsuitable for consumption **[44]**, **[48]**, **[49]**, **[50]**, **[51]**.

Microbiological indicators: Microorganisms in food can cause sensory changes in a variety of ways: when microbial growth reaches a certain threshold, a large number of specific spoilage organisms (SSO) can cause opacity in liquids or viscous, mucous surfaces, as well as colour changes, which are typical of meat and fish products. Furthermore, sensory changes caused by enzymatic reactions will result in the degradation of proteins, carbohydrates, and fats, increasing metabolites **[44]**, **[52]**, **[53]**.

A sigmoid curve characterizes microbial growth, divided into four sections: lag phase, exponential or log phase, stationary phase and decline or death phase **[44]**, as shown in Figure 3.

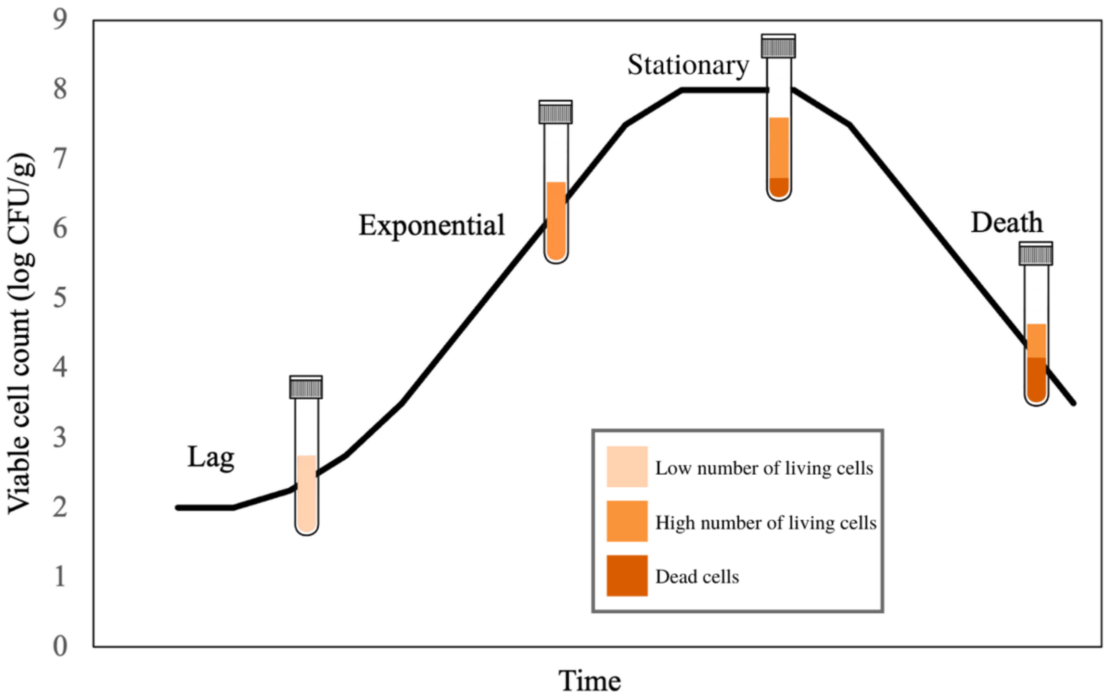

Figure 3 Microbiological growth curve.

The lag phase is the period of cell adaptation to the environment, and there is no multiplication. Increasing the duration of this phase is an important aspect of product shelf life. There are no changes in the sensory characteristics of food during the lag phase. In the exponential phase, the division of cells takes place, and the number of microorganisms grows at an exponential rate. During this phase, when the slope of the curve is at its steepest, the growth rate reaches its maximum value. Sensory characteristics change as a result of metabolic activity and microorganism growth. The stationary phase shows a decrease in cell division, resulting in some cells dying, some dividing slowly, and some ceasing to grow. The exhaustion of essential nutrients and space and the accumulation of inhibitory products cause this effect. It is also at this point that the cell count reaches its maximum amount. The death phase is characterized by the reduction in the population of microorganisms because during this stage, the number of cells dying outnumbers the number of cells born **[44]**, **[54]**, **[55]**.

Some studies indicate that odours caused by spoilage microorganisms become apparent when they reach values of 7 to 7.5 log CFU/g. The maximum number reached by spoilage organisms in fresh foods is estimated at and 10 log CFU/g **[44]**.

PREDICTIVE MICROBIOLOGY

Food safety standards in the food industry could develop risk analysis in public and private sectors to establish regulations and predictions. Applying quantitative and qualitative model systems allows prognosis and information about operations and quality, addressing the microbiological issues in food causing spoilage and health risks **[56-59]**.

Predictive microbiology is a tool used to study the behaviour of microorganisms under specific conditions for scientific analysis, as well as to determine the lifespan of products and the safety of foods **[60]**, **[61]**, **[62]**. Using mathematical models, it is possible to calculate the growth of microorganisms and draw conclusions about product quality and shelf life. This concept was first introduced in 1937 but has gained more use in recent years **[44]**, **[63]**, **[64]**.

The models used in predictive microbiology approaches have different evaluations. The most usual was the proposal by authors Whiting and Buchanan who characterized modelling as primary, secondary, and tertiary **[65]**.

The primary model elucidates the behaviour of microorganisms at a specific time under certain conditions **[56]**, **[66]**. They enable the calculation of relevant growth parameters such as maximum growth rate, lag phase duration, initial count, and maximum count of microorganisms. Most common models are modified Gompertz, Baranyi and Roberts, logistic, and three-phase linear models **[44]**, **[67]**.

Secondary models describe primary model parameters that are affected by environmental factors such as temperature, pH, and water activity. They also propose the time required to reduce the lag phase by ten times in response to changes in these factors **[44]**, **[54]**. The models used are the second-order response surface equation, the square root model, and the Arrhenius equation **[54]**. Table 1 shows an overview of various primary and secondary models used to predict the growth of microorganisms in foods, extracted from the studies of Kreyenschmidt and Ibald **[68]**.

Tertiary models generate representations from primary and secondary models and provide algorithms capable of calculating the microbial response to different applied conditions and comparing the effects of these different conditions **[73]**, **[74]**, **[75]**. There is several existing software to be used in the development of tertiary models **[44]**, **[54]**, **[56]**, **[76]**, **[77]**,

Besides the classifications above, the models can also be divided into four groups as presented in Table 2. Kinetic models predict the concentration levels of a microbial strain related to the rates of growth and death response; probability models predict the production of toxins of microorganisms and are related only to growth rate and not speed; empirical models relate two variables through polynomial equation offering a mathematical relationship between inputs and outputs; and mechanistic models allow to determine different parameters and present the effectiveness of predicted experimental conditions **[56]**.

Table 1 A correlation of various primary and secondary models (Adapted from **[44]**).

Primary Models	Equations	Source
Modified logistic model	$N(t) = A + \frac{C}{1 + e^{-B.(t-M)}}$	**[69]**
Modified Gompertz model	$N(t) = A + C.e^{-e^{-B.(t-M)}}$	**[69]**
Baranyi and Roberts model	$N(t) = A + \mu_{max}.a(t) + \ln\left[1 + \frac{\exp(\mu_{max}.a(t)) - 1}{\exp(N_{max} - A)}\right]$	**[70]**
Parameter	*N(t)* = microorganism count at a time t; *A* = lower line of the asymptotic growth curve; N_{max} = maximum population count; $C = N_{max} - A$, distinction between upper and lower lines; *B* = maximum rate of growth time *M*; *M* = time when maximum specific growth rate is achieved and *t* is time, m_{max} is maximum specific growth rate; *a(t)* = adjustment function, which takes into account the lag phase (adaptation to the new environment); *q(t)* = physiological conditions of the cells at time t.	
Secondary Models	**Equations**	**Source**
Arrhenius equation	$ln(B) = \ln F - \left(\frac{E_a}{R.T}\right)$	**[71]**
Square root equation	$\sqrt{B} = b * (T - T_0)$	**[72]**
Parameter	*B* = relative rate of growth at time *M*; *F* = preexponential factor; E_a = activation energy for the bacterial growth; *R* = gas constant; *T* = absolute temperature; *B* = slope (steepness) of the regression; T_0 = theoretical minimum cell growth temperature.	

Table 2 Classification of mathematical models in the food industry (Adapted from **[56]**).

Model category	Prediction	Publication
Kinetic	Growth or death response rate (concentration level of microbial strain)	**[78]**
Probabilistic	Toxin contaminant production by microorganisms or sporulation	**[79]**, **[80]**, **[81]**
Empirical	Interactions between inputs and outputs. A polynomial equation is used to describe a two-variable relationship.	**[82]**, **[83]**, **[84]**
Mechanistic	Prediction index under modified conditions, determination of various parameters	**[85]**, **[86]**

Predictive microbiology application in food: A selection of articles from the last ten years was conducted to verify the many applications of *predictive microbiology* analysis for microbiological contamination in different food products, as presented in Table 3. Pin and Baranyi from 1998 were also included because it was one of the initial publications presented for predictive microbiology, displaying the behaviour of several microbiological contaminants found most in meat products.

Table 3 Predictive microbiology analysis in different food products.

Food	Microorganism	References
Cantaloupe	*Listeria monocytogenes*	**[87]**
Cheese	*Escherichia coli* and *Staphylococcus aureus*	**[88]**
	Listeria monocytogenes and *Pseudomonas fluorescens*	**[89]**
Cheese - *Gorgonzola*	*Listeria monocytogenes*	**[90]**
Cheese – *Kochkäse*	Yeasts and molds, Aerobic mesophilic bacteria, and Lactic acid bacteria	**[91]**
Cheese - *Minas*	Lactic acid bacteria and *Listeria monocytogenes*	**[92]**
Cheese - *Paneer*	*Listeria monocytogenes*	**[93]**
Cheese - *Ricotta fresca*	*Enterobacteriaceae, Listeria monocytogenes,* Mesophilic lactic acid bacteria, molds, *Pseudomonas* spp.*, t*otal bacterial count, and yeasts	**[94]**
Chicken meat	Total viable count	**[95]**
	Lactic acid bacteria, *Pseudomonas,* and total viable count	**[96]**
	Salmonella	**[97]**
	Salmonella spp.	**[98]**
Ham	Lactic acid bacteria	**[99]**
	Weissella viridescens	**[100]**
Hot Pepper Sauce	*Pichia manshurica, Lactobacillus, Escherichia coli, Salmonella enterica* and *Listeria monocytogenes*	**[101]**
Infant Formula	*Salmonella spp.*	**[102]**
Lettuce	*Salmonella* spp., *Escherichia coli*	**[103]**
	Salmonella spp.	**[63]**
Meat	*Acinetobacter*, *Brochothrix*, *Carnobacterium*, *Kurthia* spp., *Lactobacillus*, *Leuconostoc*, *Pseudomonas*, *Psychrobacter*, and *Shewanella*	**[104]**
	Lactobacillus plantarum	**[105]**
	Listeria monocytogenes and *Pseudomonas putida*	**[106]**
Meat - *Morcilla*	*Leuconostoc mesenteroides and Weissella viridescens*	**[107]**
Milk	*Listeria innocua*	**[108]**

Table 3 Continue.

Food	Microorganism	References
	Listeria monocytogenes and *Pseudomonas putida*	**[109]**
Mushroom – *Agaricus bisporus*	*Pseudomonas* spp.	**[110]**
Octopus	*Enterobacteriaceae*, *Pseudomonas* spp., total viable count	**[38]**
Pork meat	*Salmonella*	**[111]**
Potato Salad	*Salmonella* Enteritidis	**[112]**
Poultry	*Listeria monocytogenes* and *Pseudomonas fluorescens*	**[89]**
Rice	Molds, Aerobic plate count	**[113]**
Salmon	*Listeria monocytogenes*	**[89]**
Scrambled egg mix	*Salmonella*	**[114]**
Tomato	*Bacillus coagulans*	**[115]**

Predictive microbiology software: Tertiary models are applied in software that generates the model response in equations and graphs. There is a range of software with different databases and applications; a few of them are described in various articles, as presented in Table 4.

Table 4 Use of predictive microbiology softwares.

Software	Study	Reference
ComBase	Use of ComBase data to develop an artificial neural network model for nonthermal inactivation of *Campylobacter jejuni* in milk and beef and evaluation of model performance and data completeness using the acceptable prediction zones method	**[116]**
DMFit	The suitability of the ISO 11290-1 method for the detection ofListeriamonocytogenes	**[117]**
GinaFit	GInaFiT, a freeware tool to assess non-log-linear microbial survivor curves	**[118]**
IPMP Global Fit	IPMP Global Fit – A one-step direct data analysis tool for predictive microbiology	**[77]**
MicroFit	MicroFit: free software for the development and adjustment of mathematical models of bacterial growth	**[76]**
MicroHibro	'MicroHibro': A software tool for predictive microbiology and microbial risk assessment in foods	**[73]**
ValT	Validation software tool (ValT) for predictive microbiology based on the acceptable prediction zones method	**[119]**

Software is presented online or as an extension for Microsoft Office Excel. Each program contains a unique database for equations and models presented and validated by various authors **[120]**. The most common one used online, with a complete database, is ComBase, as shown in Figure 4. ComBase allows its users to insert research data, demonstrates changes in microbiological curves with extrinsic parameters change and compares with existing data in software (Figure 5).

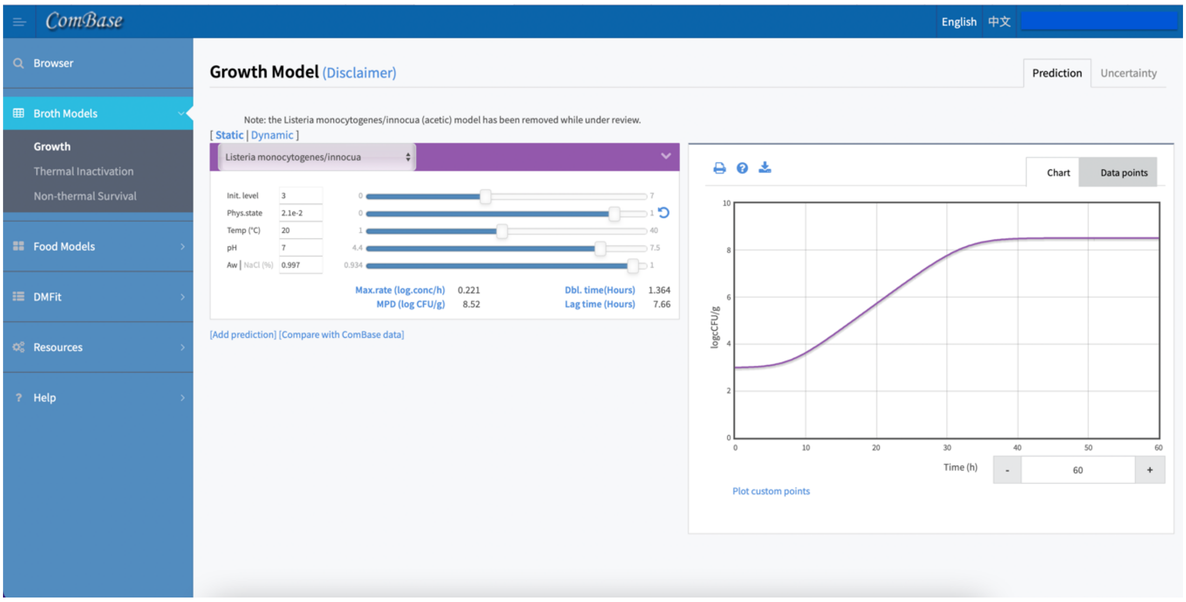

Figure 4 Interface of ComBase software.

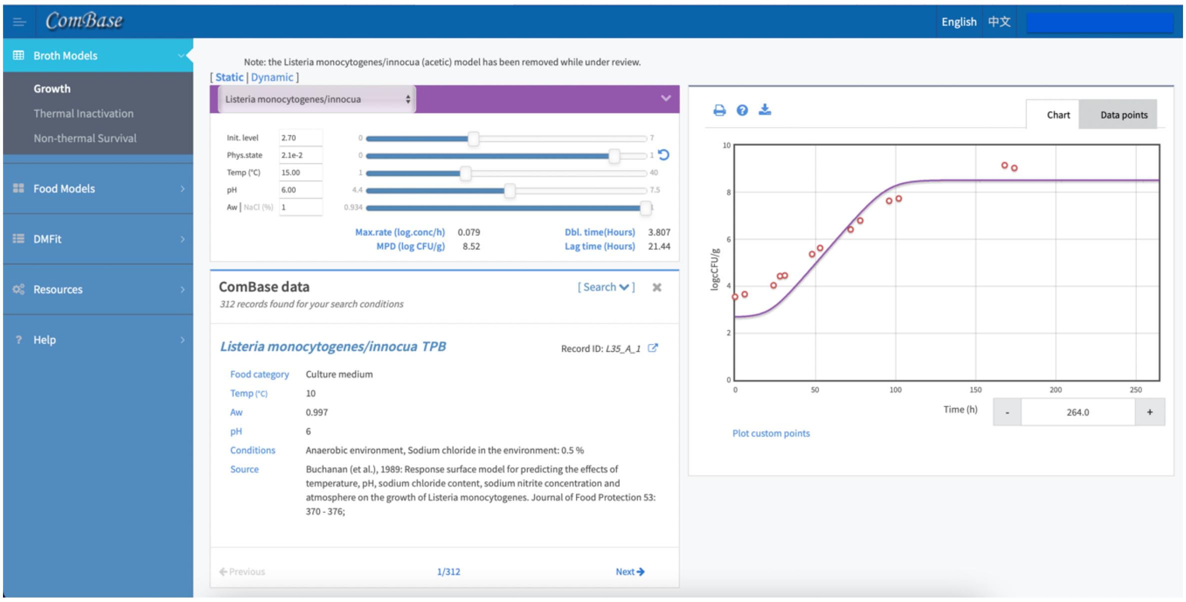

Figure 5 Interface of ComBase software with growth prediction and comparison with ComBase data.

Alternatively, software for Microsoft Excel has limited usage, but it is still one of the significant tools for calculating the parameters of the equation. GinaFit (Figure 6) presents several fixed models in which the user just needs to create a sheet with the data obtained in research, and, according to the model, results are presented. The reference for the model used is also presented **[120]**.

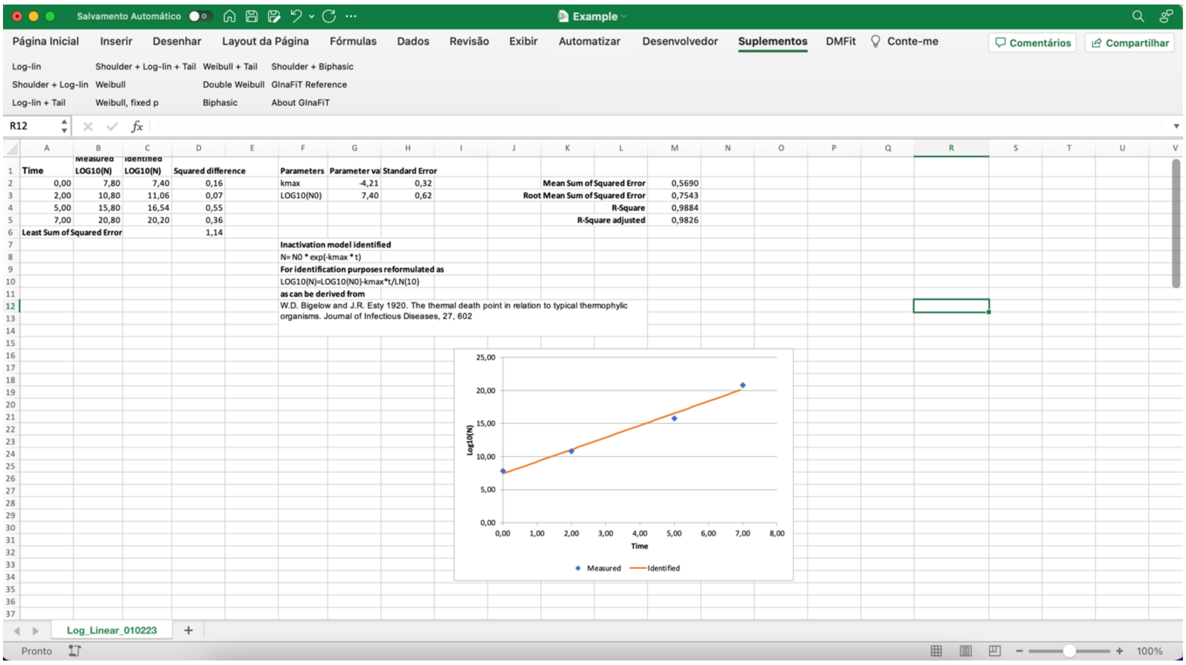

Figure 6 Interface of GinaFit within Microsoft Excel.

CONCLUSIONS

Food safety and food security are very important for public health. Predictive microbiology tools, using mathematical models to estimate microbial growth and behavior, are being used to prevent food contamination and foodborne illness diseases. The risks of unsafe food distributed to consumers could bring several problems to worldwide governments and organizations, as food safety and security are treated as public health issues and responsibilities. Predictive microbiology, a tool that was first addressed in 1937, has gained strength over the last twenty years between industry and academia, and can be utilized to establish a product shelf-life to reduce contamination from pathogenic and spoilage microorganisms. Acknowledging possible microbial contamination could reduce the problems regarding food safety and the waste of food that is generated annually. With safer food and waste reduction, food security becomes a closer reality for all people, as it should be according to the guidelines from FAO. Many studies have been conducted on different microorganisms in many food products. The approach between university and industry should be a reality to help prevent and solve the food safety and security problem, especially in economically developing nations, where food insecurity is often related to a lack of knowledge.

Food security is the state achieved when all people have the social and economic means to access safe, nutritious, and culturally acceptable food that meets their dietary requirements and preferences for an active and healthy life at all times. It is a complex issue influenced by various factors, including economic, environmental, technological, and geopolitical challenges. To address food security concerns, the concept is often based on four pillars: food availability, physical and economic access to food, food usage based on cultural and nutritional needs, and food stability. Achieving food security requires the involvement of all stakeholders, including policymakers, producers, distributors, and consumers.

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Funds:

The authors gratefully acknowledge the financial support received from the Ministry of Science, Technology, Innovation and Communications and National Council for Scientific and Technological Development – CNPQ (CNPq / MAI-DAI CP n. 12/2020). The study is funded from Coordination of Superior Level Staff Improvement – CAPES (finance code 001) and Foundation for Research and Innovation of the State of Santa Catarina – FAPESC (TO 2018TR342).

Acknowledgments:

The authors gratefully acknowledge to Coordination of Superior Level Staff Improvement – CAPES, Fundação Universidade Regional de Blumenau – FURB and Nidec Global Appliance are also properly acknowledged. Thanks to Professor Cyntia Bailer for the language revision.

Conflict of interest:

There is no conflict of interest, according to the authors.

Ethical statement:

This article does not contain any studies that would require an ethical statement.

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